Hybrid Eulerian and Lagrangian Simulation of Steep and Breaking Waves and Surface Fluxes in High Winds

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LONG-TERM GOAL

This research aims at developing a hybrid numerical capability using a Lagrangian Smoothed Particle Hydrodynamics (SPH) method and an Eulerian Level-Set Method (LSM) for the simulation of steep and breaking waves in high winds. The ultimate goal is to establish an advanced computational framework for the investigation of wind-wave breaking in air-sea interaction processes, including the airflow separation over steep and breaking waves, the wind–wave momentum and energy transfer, the momentum and energy injection from breaking waves to the upper ocean, and the turbulence transport of scalars.

OBJECTIVES

The scientific and technical objectives of this research are:

(1) develop a hybrid Eulerian and Lagrangian multi-fluids simulation capability, which combines the SPH and LSM with environmental input provided by WIND-SNOW (the merger of wind LES with the wave model of Simulation of Nonlinear Ocean Wave (SNOW));
(2) use the numerical method developed in (1) to simulate wind-wave-ocean interactions at small scales to elucidate flow structure;
(3) quantify and characterize wind–wave momentum and energy transfer and the injection to the upper ocean by breaking waves; and
(4) simulate scalar transport near steep and breaking waves to identify key transport processes.

APPROACH

This research builds on a hybrid simulation approach that couples several Eulerian and Lagrangian methods for free-surface turbulence and wave simulation. The WIND–SNOW is used to simulate

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wind turbulence and wavefield, with the phases of nonlinear waves resolved, to provide realistic environmental input for the simulation of breaking waves. In WIND–SNOW, LES of air turbulence is performed by using a hybrid pseudo-spectral and finite-difference method on a boundary fitted grid that follows the ocean wave surface; a high-order spectral (HOS) method is used to capture all of the dynamically important nonlinear wave interactions in the wavefield; and the wind and wave simulations are dynamically coupled through a fractional step method with two-way feedbacks.

As a wave becomes steep, LSM in a subdomain that contains the steep/breaking wave is performed to better resolve the flow field. LSM uses a signed distance function, namely the level-set function, to represent the interface implicitly. The location where the level-set function has zero value denotes the air–water interface. In the simulation, air and water together are treated as a fluid system with varying density and viscosity. In LSM, the level-set function is advected by the flow subject to a Lagrangian-invariant transport equation. To preserve the distance-function property for the level-set function, re-initialization is performed during the simulation using a sub-cell fix method. A Coupled Level-Set Volume-of-Fluid (CLSVOF) method is employed to conserve the mass precisely.

When the wave breaks, the flow at the free surface may become very violent, air and water may be highly mixed, and drops and bubbles may be formed. To better resolve the detailed structures and to robustly capture the violent flow, the SPH method is used, which is ideal for the wave breaking problem as the motion of nodal points (i.e., smoothed particles) is tracked in a Lagrangian manner.

For WIND–SNOW and LSM, the codes are parallelized using message passing interface (MPI) based on domain decomposition. For SPH, graphics processing unit (GPU) computing, which is highly efficient for particle methods, is used to speed up the simulation.

WORK COMPLETED

This project started during the fiscal year of 2010. In this first phase of the project, extensive developments and tests have been performed for the codes, and encouraging results have been obtained in preliminary simulations, which include:

- Further development of LSM and SPH algorithms, use of the strength of volume-of-fluid and ghost-fluid methods to improve the performance of LSM, systematic assessment of SPH performance.
- LSM simulation of the interaction of strong turbulence with a free surface with violent free-surface motions captured, analysis of Reynolds stress balance and turbulence kinetic energy budget in wave breaking.
- Simulation of the viscous dissipation of plane progressive water wave using SPH, comparison with the analytical result.
- Simulation of wave breaking using SPH, illustration of different water particle motions in breaking waves.
- Investigation of turbulence simulation using SPH, characterization of Lagrangian statistics of turbulence, and identification of fluid particle motion associated with turbulence vortex structure.

RESULTS

During the first phase of this project, substantial developments have been made in the LSM and SPH simulations of free surface flows. Encouraging results have been obtained. Figure 1 shows an example of LSM simulation of a violent wave breaking event. Figure 1(a) shows a snapshot of the water jet reentering the surface and bouncing back. The overturning water jet has a complex three dimensional structure. Fingers are formed at the tip of the jet due to flow instability. Preliminary analysis on the effect of wave breaking on Reynolds stress and turbulence kinetic energy budget has been performed. As an example, figure 1(b) shows the horizontal transport of the horizontal Reynolds stress on a vertical cut through the breaking wave. Significant transport is observed in the reentering region. In figure 1(c), energy dissipation on the same cut as in figure 1(b) is quantified. It shows the presence of high dissipation, which is caused by the strong shear generated by the breaking wave. The above results illustrate the robustness of the LSM for simulating violent free-surface flows, and show the importance of wave breaking in energy transport and dissipation.

Systematic developments of SPH have been made. Figure 2 shows an example of the investigation on viscous dissipation of waves. The decay of an Airy wave with an initial wave slope $ak = 0.1$ is simulated. After 16 wave periods, the high viscosity in the fluid reduces the wave amplitude by one order of magnitude. The contours of velocity components plotted in figures 2(a) and (b) show that the wave motion is still captured by the SPH method after such long duration of simulation with significant wave damping. The decay of wave amplitude in time is plotted in figure 2(c), which agrees with the theoretical result of exponential decay.

Being a particle method, SPH captures water parcels naturally and is especially suitable for the study of breaking waves. In the case shown in figure 3, a two dimensional sinusoidal wave with initial wave slope $ak = 0.55$ is simulated with a relatively low resolution as a preliminary study. Two snapshots of the particles are presented in figures 3(a) and (b). The free surface is sharp at most of the places except for the breaking region where dispersed water parcels are generated. The trajectories of two particles are plotted in figures 3(c) and (d), respectively. Particle A is located far away from the breaking wave crest. It has an orbital motion, of which the radius decreases due to viscous dissipation. Particle B is located at the breaking crest. It starts with a circular motion. After it reaches the wave crest, it moves forward with the breaking jet, falls down to the water, and then bounces up with a splash. The above results are consistent with the observations in literature.

Turbulence plays an essential role in wind–wave interaction. Numerical study of turbulence using SPH is rare in the literature. To examine the performance of SPH in turbulence simulation, isotropic and homogeneous turbulence generated by a linear forcing method (Lundgren 2003; Rosales & Meneveau 2005) is simulation. In figure 4(a), (b) and (c), contours of the three velocity components at the same time are plotted. Coherent vortex structures are identified. In figure 4(d), the trajectory of a particle is plotted. Spiral motion is observed, which indicates a trapping event in a vortex. In figure 4(e), the Lagrangian autocorrelation function is plotted. It can be fitted by an exponential function. The Lagrangian integral characteristic time is about 78% of large-eddy turnover time, which is close to the value obtained by Yeung & Pope (1989) using Eulerian simulation.

IMPACT/APPLICATION

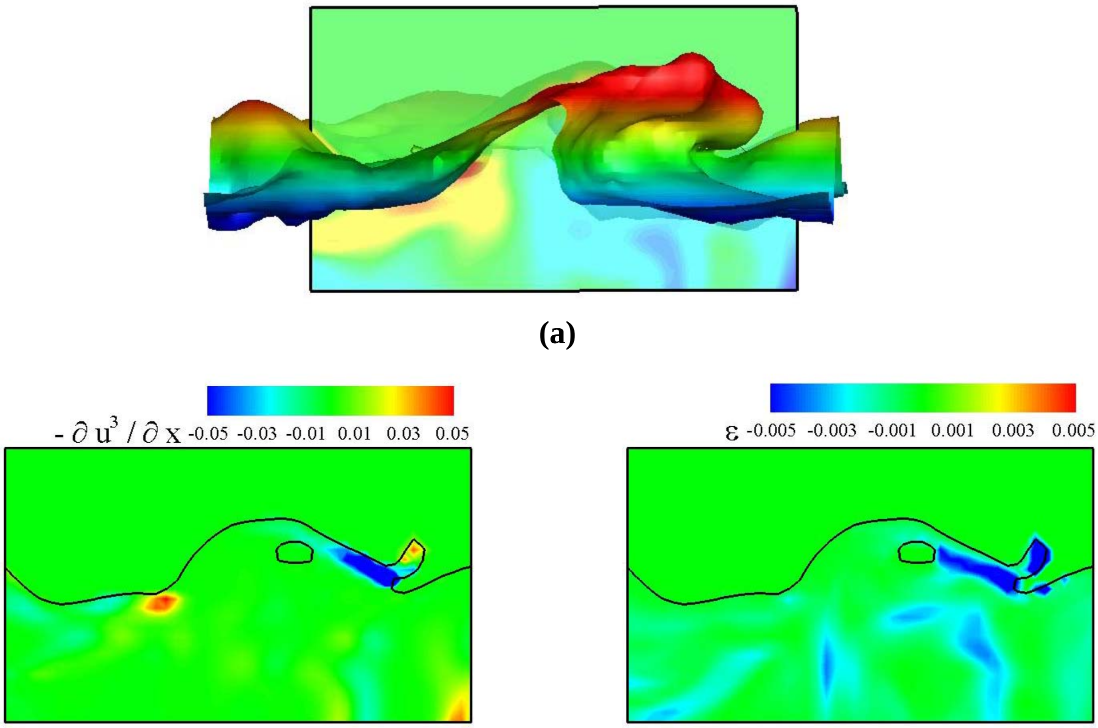
This project aims at developing an advanced simulation tool for multi-fluids free-surface flows that can be used to study the fundamental physics of wave breaking. The research will improve the understanding of air-sea interaction dynamics. The numerical developments in this project are expected to substantially improve the accuracy and efficiency of breaking wave simulation, which will lead to a powerful computational capability for direct comparison of measurement and modeling.

REFERENCES

Lundgren T. S. 2003 “Linearly forced isotropic turbulence,” *Annual Research Briefs, Center for Turbulence Research, Stanford*, 461-473.

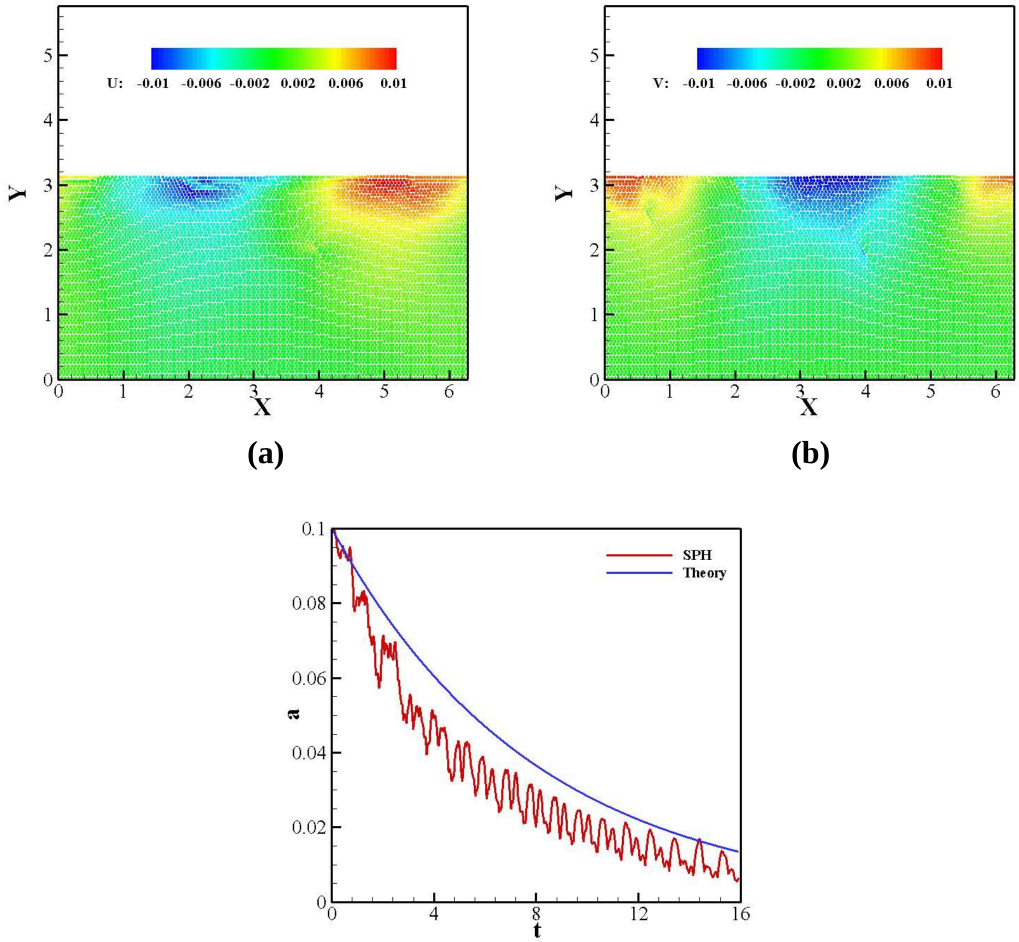
Rosales C. & Meneveau C. 2005 “Linear forcing in numerical simulations of isotropic turbulence: Physical space implementations and convergence properties,” *Phys. Fluids* **17**, 095106.

Yeung P. K. & Pope S. B. 1989 “Lagrangian statistics from direct numerical simulations of isotropic turbulence,” *J. Fluid Mech.* **207**, 531-586.



(a) **(b)** **(c)**

Figure 1. LSM simulation of wave breaking: (a) snapshot of the breaking free surface and a vertical cut with horizontal velocity contours; (b) horizontal transport of the horizontal Reynolds stress associated with the wave breaking; and (c) energy dissipation associated with the wave breaking. Only a small subdomain of the computation is shown.



(a) **(b)**

(c)

Figure 2. SPH simulation of viscous damping of a plane progressive wave: (a) and (b), contours of velocity components u and v after 16 wave periods; (d) wave amplitude versus time (normalized by wave period) and the comparison with theory.

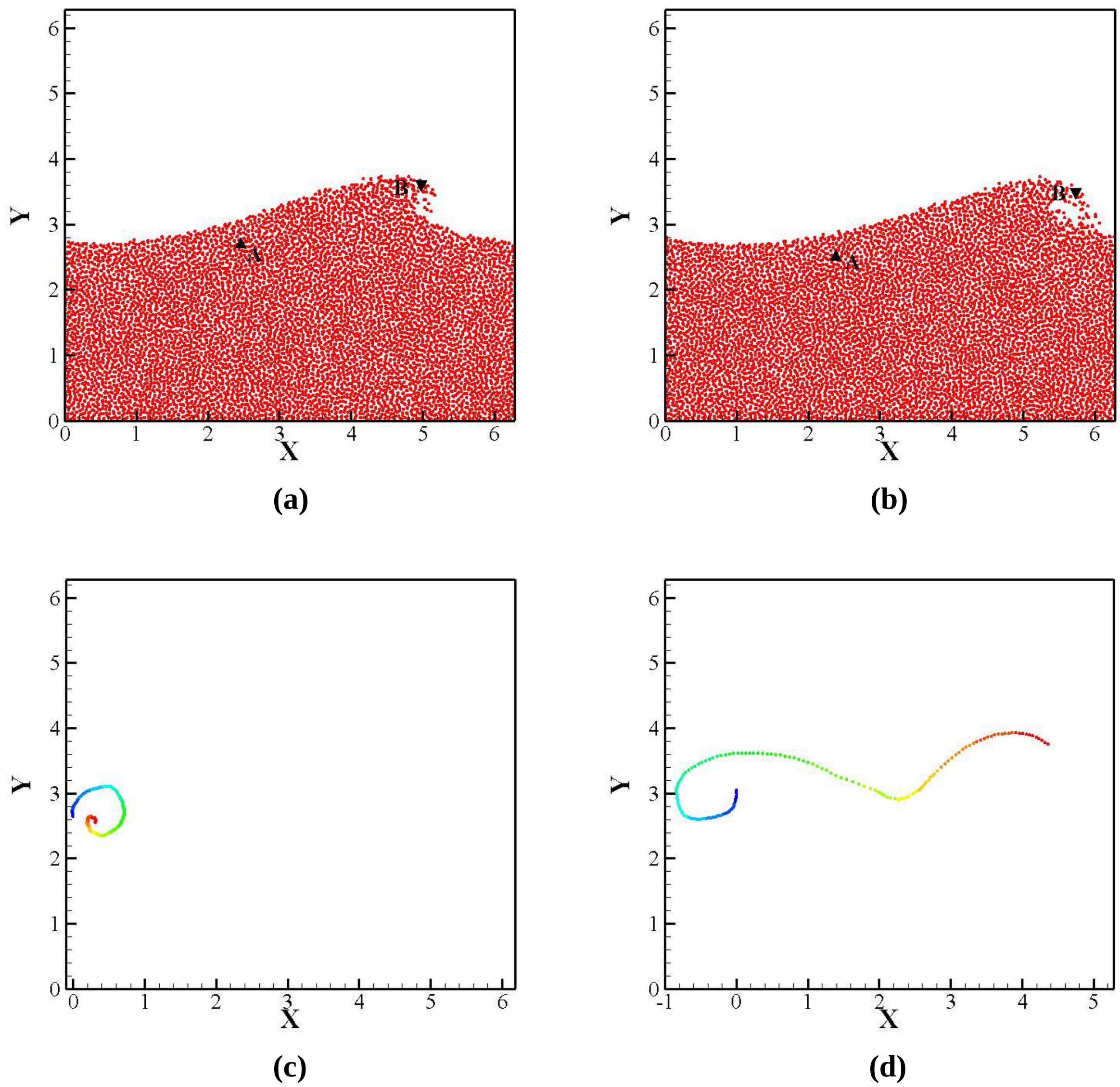


Figure 3. SPH simulation of a two dimensional breaking wave: (a) and (b), snapshots of the breaking wave at two instances; (c) trajectory of particle A; (d) trajectory of particle B. In (c) and (d), initial coordinates of A and B are reset to (0,0); the color on the trajectory indicates time, with blue and red representing the early and later time, respectively.

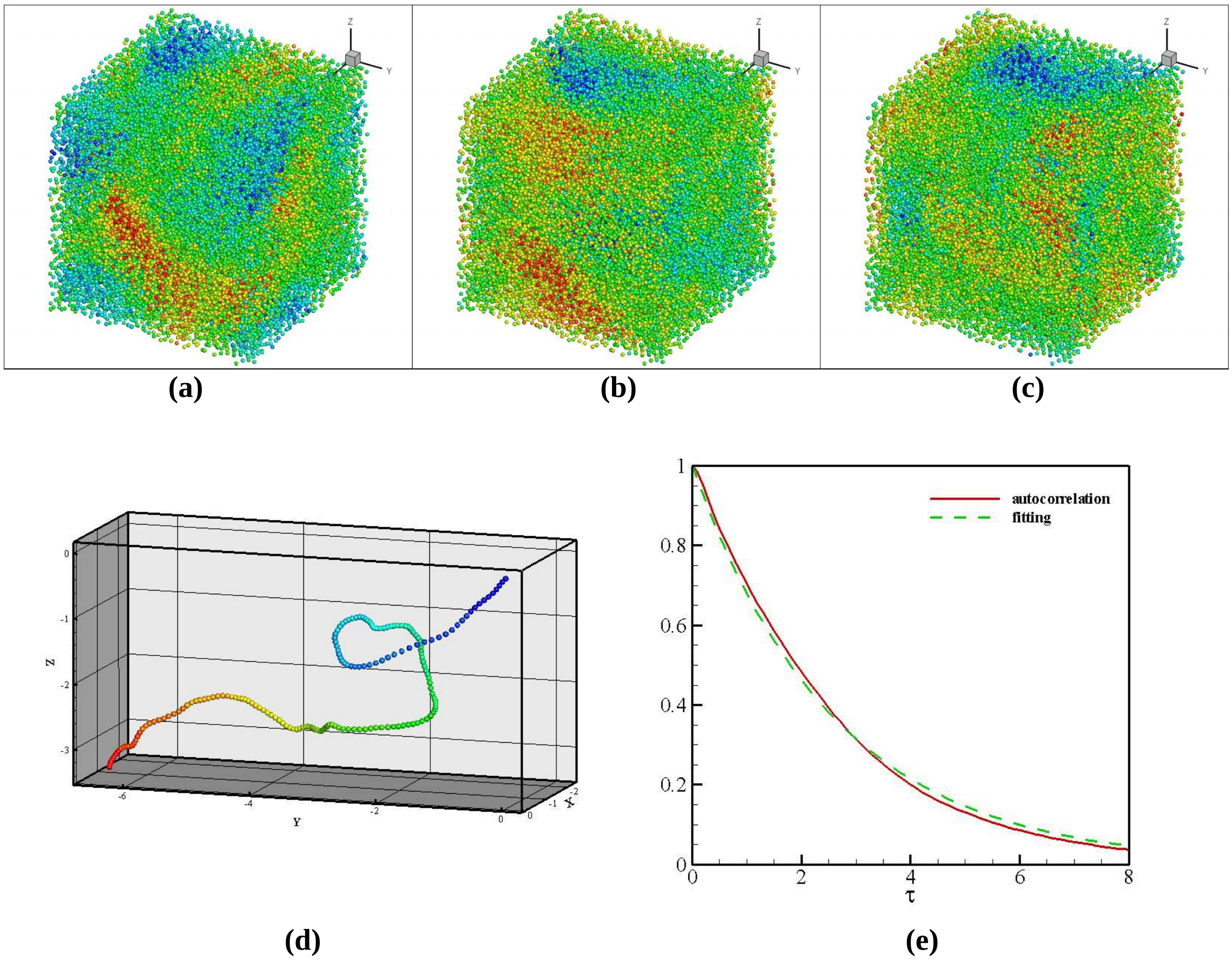


Figure 4. SPH simulation of 3D isotropic homogeneous turbulence: (a), (b), and (c), velocity contours of u, v, and w; (d) trajectory of a particle (the color on the trajectory indicates time, with blue and red representing the early and later time, respectively); (e) Lagrangian autocorrelation function $C(\tau)=\frac{<\vec{v}(t+\tau)\cdot\vec{v}(t)>}{<v^2>}$ ***and its exponential fitting by*** $\exp(-\tau/T_L)$ ***;*** T_L ***is the Lagrangian integral characteristic time and is approximately 78% of the large-eddy turnover time .***